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ABSOLUTE PHOTON YIELDS OF LIGHT ELEMENTS BY DEUTERON BOMBARDMENT

by Anthony J. Caruso and Robert A. Walter

Electronics Research Center

Cambridge, Mass.

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SUMMARY

Absolute measurements of K x-ray quantum yields resulting from deuteron bombardment of thick targets containing the elements carbon and boron were made. Characteristic x-rays for deuteron energies ranging from 0.75 to 1.3 MeV were analyzed by pulse-height distributions obtained with a proportional counter. The proportional counter contained a Mylar-aluminum window for carbon radiation and a polypropylene window for boron radiation and was operated with P-10 gas (90% argon + 10% methane) flowing at atmospheric pressure. Deuterons were incident normal to the target surface and the photons were detected at 45° to the target.

Carbon K pulse-height distributions produced by electron and deuteron bombardment of thick targets are presented to illustrate the absence of bremsstrahlung when deuteron bombardment is used. The results of the photon yields for carbon K ranged from 0.567 x 10^{-4} at 0.75 MeV to 3.17 x 10^{-4} photons per deuteron per steradian at 1.3 MeV; and for boron K, from 0.394 x 10^{-4} at 0.75 MeV to 1.15 x 10^{-4} photons per deuteron per steradian at 1.3 MeV. In all measurements, the uncertainty was less than 10 percent.

INTRODUCTION

The efficiency of characteristic x-ray production from thick targets due to electron, ion, and photon bombardment has been studied for the past 30 years or more by a handful of investigators. Since a great deal of effort has been put into efficiency measurements of x-rays due to electron and ion bombardment, the following brief historical background will be limited to these two methods.

Efficiency measurements of characteristic x-rays produced by electron bombardment of thick target elements, atomic no. $Z > 4$, with accelerating voltages as high as 40 kV have been made by Wisshak (1930) (ref. 1), Braxton et al (1945) (ref. 2), Kirkpatrick and Baez (1947) (ref. 3), Dyson (1959) (ref. 4), Campbell (1963) (ref. 5), and Caruso and Neupert (1965) (ref. 6). In all cases the measurements were made with electrons incident either normal to the target, or at 45° with respect to the normal, and with an x-ray photon take-off angle generally at 45°.

The production of x-rays by ion bombardment has been investigated since 1913. The first observation and identification of characteristic x-rays of many elements exposed to alpha-particles from radio-active sources were reported by Chadwick et al (ref. 7). In 1933, low energy characteristic x-rays from the K shell of magnesium and aluminum were produced by proton bombardment (ref. 8). Peter made the first absolute K shell efficiency measurements of aluminum with a proton energy of 132 keV (ref. 9). In his experiment protons were incident normal to the target surface, and the low energy x-rays were detected on the opposite face of the target material. Livingston, Genevese, and Konopinski studied x-rays from elements Z = 12 to 82 with proton energies up to 1.76 MeV using an ionization chamber as a detector (ref. 10). In 1941, Cork bombarded about 35 elements distributed throughout the periodic table with 10 MeV deuterons and detected the x-rays with photographic plates (ref. 11). He chose copper from among the 35 elements and determined its efficiency as a function of bombarding energy.

This area of work remained essentially dormant for the next 12 years. In 1953, Lewis et al published work on the absolute intensities of Ag, Ta, Au, and Pb using proton energies from 1.7 to 3.0 MeV (ref. 12). It was not until recently that x-rays had been studied for elements with an atomic number less than 6. Kahn et al reported absolute x-ray yields of carbon (Z = 6) for proton energies from 15 to 110 keV (ref. 13). In their experiment the protons were incident at 45° to the normal of the target and the photons were detected by a proportional counter at 45° to the target surface.

The present experimental results extend the absolute photon yield measurements to Z = 5 for ion bombardment. We believe that our results from deuteron bombardment of thick targets containing the elements carbon and boron constitute the first absolute photon yield measurements on these materials in the energy range 0.75 to 1.3 MeV. Aside from the yield measurements, the experimental results indicate a clean emission band spectrum characteristic of the element bombarded, essentially free of bremsstrahlung (continuum radiation). Coupled with the high x-ray intensities, this advantage is of great importance to the absolute calibration of soft x-ray instrumentation used to study phenomena occurring in the sun and other stars. A compact instrument capable of producing protons or deuterons with energies as high as 600 keV would be most suitable for absolute x-ray intensity calibration of laboratory and flight-type x-ray instrumentation.

EXPERIMENTAL APPARATUS

The system utilized to measure the absolute photon yields of elements is illustrated in Figure 1 and consists of a High Voltage Engineering Corporation 2.0 MeV Van de Graaff generator, an analyzing magnet, an electrostatic focusing device, a target chamber, a proportional counter, and an associated electronic recording system.

Deuterium gas is admitted into the ion source by a remotely controlled valve on the gas cylinder, and radio frequency power ionizes the gas in the ion source bottle. A positive potential is applied to the ejection electrode of the source causing the positive ions to be withdrawn from the plasma into the acceleration tube. The positive ions are focused into a well collimated beam as they are accelerated through the tube with the energy determined by the voltage of the generator. A VacIon pump maintains the accelerator tube system at a pressure of 10^{-6} torr to minimize collisions between the accelerated ions and gas molecules in the tube. For precise measurement and control of the ion beam energy, the beam is deflected through 90^{o} by an analyzing magnet which was calibrated by the Li^{7} (p,n) reaction (ref. 14). The ion beam proceeds through an electrostatic focusing tube and is focused at the target surface to a beam size of 0.5 by 1 mm. The ion beam entrance to the target chamber contains a slit system consisting of three slits. The slit adjacent to the target chamber entrance is maintained at a high negative potential to prevent secondary electrons produced in the focusing tube from entering the chamber. The chamber pressure is 10^{-5} torr and is kept essentially free of oil contamination by a liquid nitrogen trap placed above the diffusion pump.

Characteristic x-rays were detected by a conventional side window, flow-type proportional counter 6.0 cm long and 2.52 cm diameter with an anode wire diameter of 0.0466 mm. The proportional counter was mechanically attached to the target chamber through an O-ring seal and was electrically connected to a preamplifier which drives a linear amplifier having a rise time of 0.2 μsec and a minimum input sensitivity of 5 mV. The output of the linear amplifier is fed into a

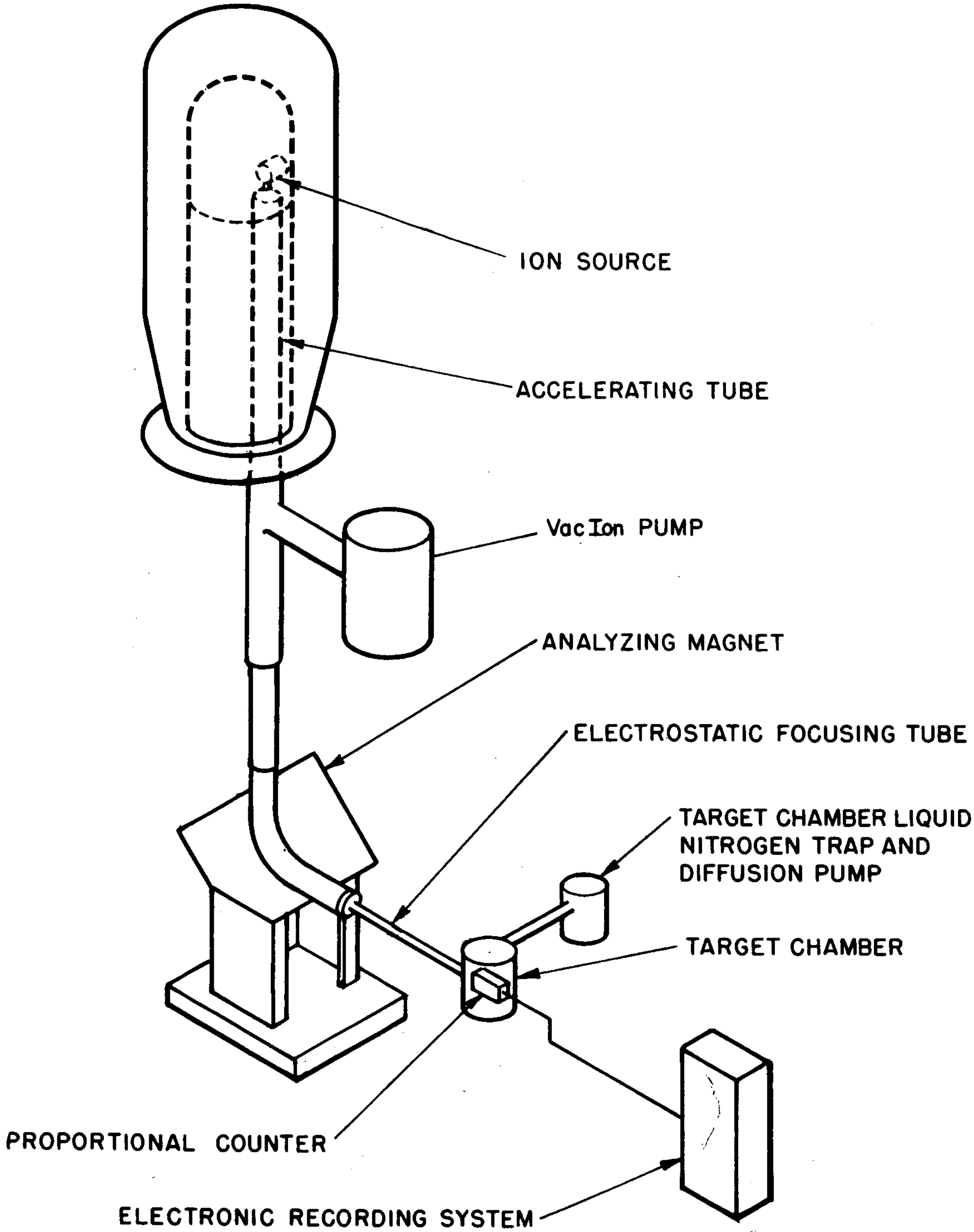

Figure 1.-Schematic diagram of the experimental apparatus

multichannel pulse-height analyzer, and the count rate is read out on a scaler.

EXPERIMENTAL MEASUREMENT

When deuterons or other ions bombard a target material, electrons are ejected from the atomic shells of the target atoms. If an impact removes an electron from the K shell, the filling of the vacancy leads to the emission of x-rays characteristic of the element being bombarded.

In the present experiment deuterons were incident normal to the target surface producing K-band x-rays characteristic of carbon K (44Å) and boron K (67Å) radiation. Carbon K-band radiation was obtained from a diamond 0.125 inch thick and essentially free of surface defects. Boron K radiation was obtained from boron powder (99.50% pure) evaporated onto tantalum substrates to a thickness of 1.0 to 2.0 microns. The boron target surfaces were very smooth and free of any pits. X-rays characteristic of the target material were detected in a solid angle of 1.68 x 10^{-4} sr at a photon take-off angle of 45^{o} to the normal of the target surface.

To measure absolute photon yields, it is necessary to record all the x-rays emitted from the target in the solid angle subtended by the counter. This was accomplished by operating the detector with P-10 gas (90% argon + 10% methane) flowing through the proportional counter and recording the photon count rate in the Geiger region as a function of detector gas pressure. The results showed no appreciable increase in photon count rate for detector gas pressures greater than 40 torr indicating 100 percent absorption efficiency of soft x-ray photons (ref. 15).

The absolute efficiency of the detector was determined by measuring the transmission of the detector window materials. Carbon K (44Å) measurements were made with a Mylar-aluminum window approximately 6.0 microns thick. Since the Mylar-aluminum window was opaque to boron K (67Å) radiation, stretched polypropylene approximately 5000Å thick was used at this wavelength. The transmission of the detector windows was measured directly by mounting a polypropylene window of arbitrary transmission on the detector and inserting the windows ultimately to be used between it and the x-ray source. The ratio of the x-ray intensities measured with the windows in and out of the x-ray beam gave the transmission. This procedure was carried out at several deuteron energies giving an average transmission of 4.49 ± 0.05 percent for aluminum-Mylar, and 55.00 ± 3.00 percent for stretched polypropylene with a thin, evaporated film of aluminum. The thin, evaporated film of aluminum on the polypropylene is necessary to eliminate electrostatic charges that build up on the surface of the detector window, which otherwise would cause the detector to respond erratically.

To make the window materials compatible with the detector, a slight modification of the proportional counter was necessary. The supporting assembly of the counter window was replaced by a specially fabricated brass disk coated with nickel and having an aperature 0.252 mm wide and 16.16 mm high. The thin Mylar and polypropylene window materials, whose transmissions were previously determined, were each placed over separate disks. The disks were fastened to the proportional counter by means of an O-ring seal, and the proportional counter was attached to the target chamber.

The characteristic K-band radiation for each element was analyzed by a 400-channel pulse-height analyzer, and the pulse-height distributions were recorded on tape. Figure 2 shows the pulse-height distributions of carbon K, boron K, and beryllium K x-radiation for a deuteron energy of 1.2 MeV. However, the beryllium target was obtained quite late in the experiment, when the time available for use of the accelerator was severely limited. Consequently, only a pulse-height distribution of beryllium K radiation was obtained, and no transmission measurements could be performed. An attempt was made to arrive at the transmission of polypropylene for beryllium K radiation by extrapolating a curve of transmission versus wavelength using the experimental points for carbon K and boron K radiation. This extrapolation indicated decreasing transmission with decreasing atomic number and led one to expect that the transmission of a particular polypropylene window would be less for beryllium K radiation than for boron K radiation. However, the intensity of beryllium K radiation measured with the detector having a polypropylene window preiously calibrated for carbon and boron K radiation was far too high. This result suggests that an absorption edge exists between 67 and 113Å for polypropylene. The extrapolation procedure is therefore invalid, and the beryllium K photon yield could not be determined in this manner.

In addition to the characteristic x-rays produced by electrons or ions in a target, a continuous x-ray spectrum appears as a result of bremsstrahlung, i.e., radiation due to the deflection of the incident particle in the coulomb fields of the target nuclei. In the case of targets of low atomic

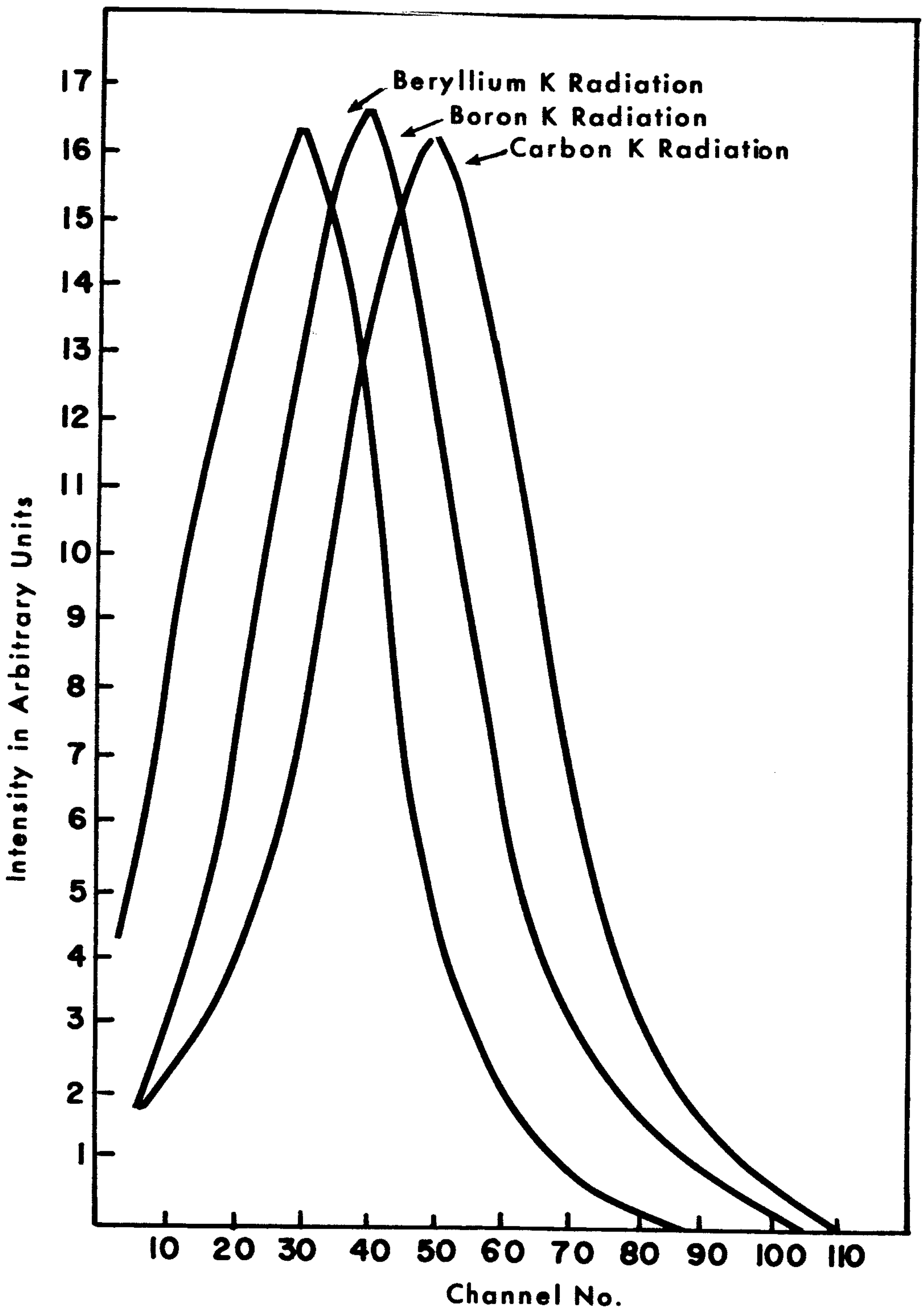

Figure 2.-Pulse-height distribution curves

number, ion bombardment produces considerably less bremsstrahlung than electron bombardment. A comparison of the pulse-height distributions of carbon K for excitation by 2.5 keV electrons and 1.2 MeV deuterons is shown in Figure 3. Both carbon K pulse-height distributions were recorded using a Mylar-aluminum window in the detector, and the peaks of the curves were adjusted to be equal. The bremsstrahlung is exaggerated because the transmission of the window for the bremsstrahlung is much higher than the transmission for the carbon K-band. It is clear from the curve of Figure 3 that the pulse-height distribution due to deuteron bombardment, designated by the continuous line curve, is essentially free of bremsstrahlung. This feature is very advantageous in that it eliminated the laborious task of separating the bremsstrahlung from the characteristic x-rays, which is encountered in electron bombardment.

RESULTS AND CONCLUSIONS

The resultant absolute photon yield measurements for carbon K and boron K are shown in Figure 4. These values were determined with a knowledge of the pulse-height distributions, absorption efficiency of the detector gas, transmission of the counter windows, deuteron energies, beam current, solid angle subtended by the detector aperture, and photon counting rate. Carbon K and boron K measurements were made for deuteron energies from 0.75 to 1.3 MeV at 0.05 MeV intervals with an overall uncertainty of less than 10 percent.

Previously reported experimental work indicates that the photon yield for proton bombardment increases with decreasing atomic number (ref. 16). In the present investigation, however, reversal of this condition was observed for the yields of boron K and carbon K radiation at higher accelerating voltages. Figure 4 shows the boron K yields to be lower than carbon K by a factor of 1.49 at 0.75 MeV and by 2.82 at 1.30 MeV. It appears that the same phenomenon occurs for electron bombardment of thick targets of boron and carbon, where the yield cross-over occurs between 6.0 and 9.0 kV (ref. 5).

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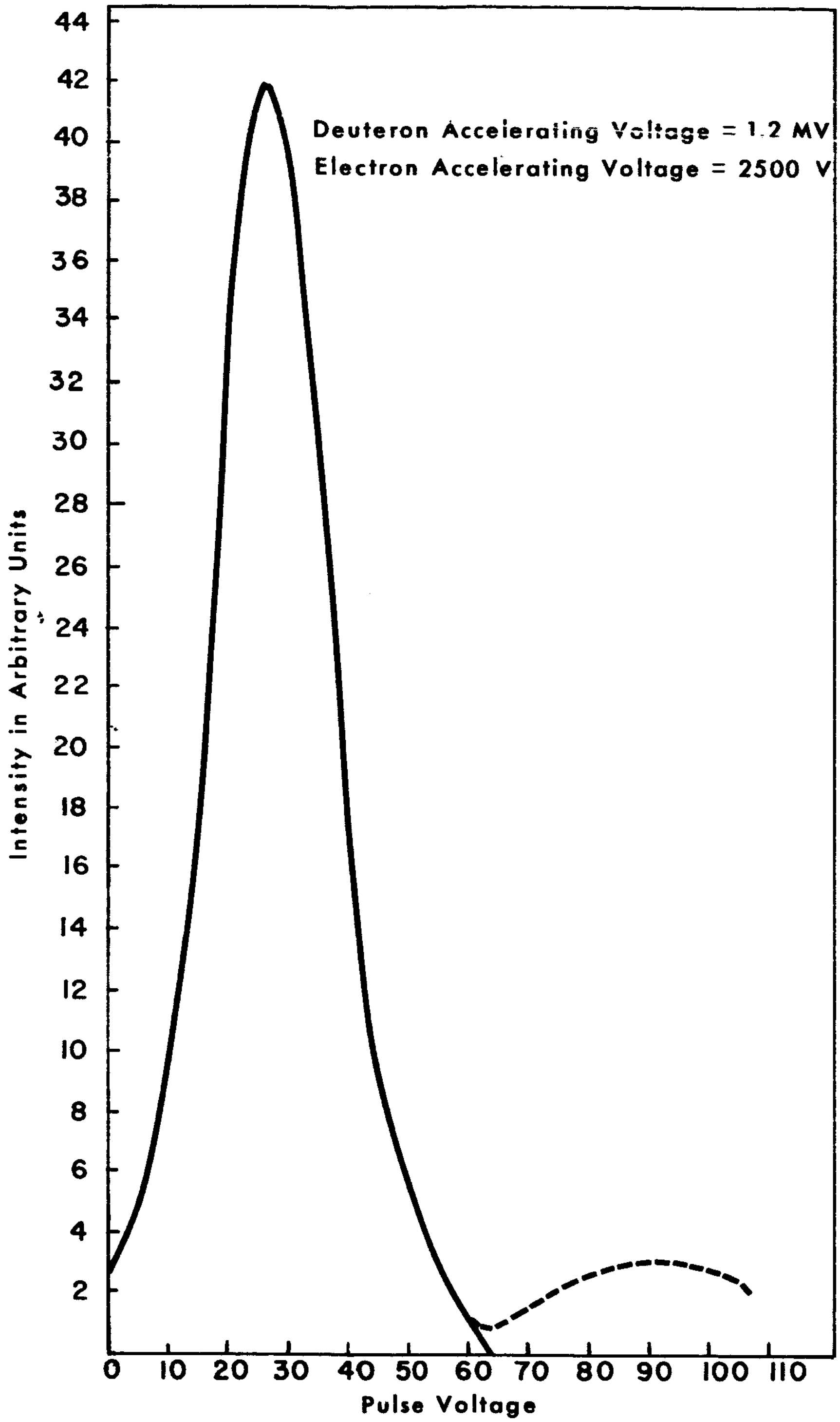

Figure 3.-Comparison of carbon K pulse-height distributions produced by electron and deuteron bombardment. Note the bremsstrahlung, designated by the dashed curve, due to electron bombardment which is absent for deuteron bombardment. An aluminum-Mylar window was used for both measurements.

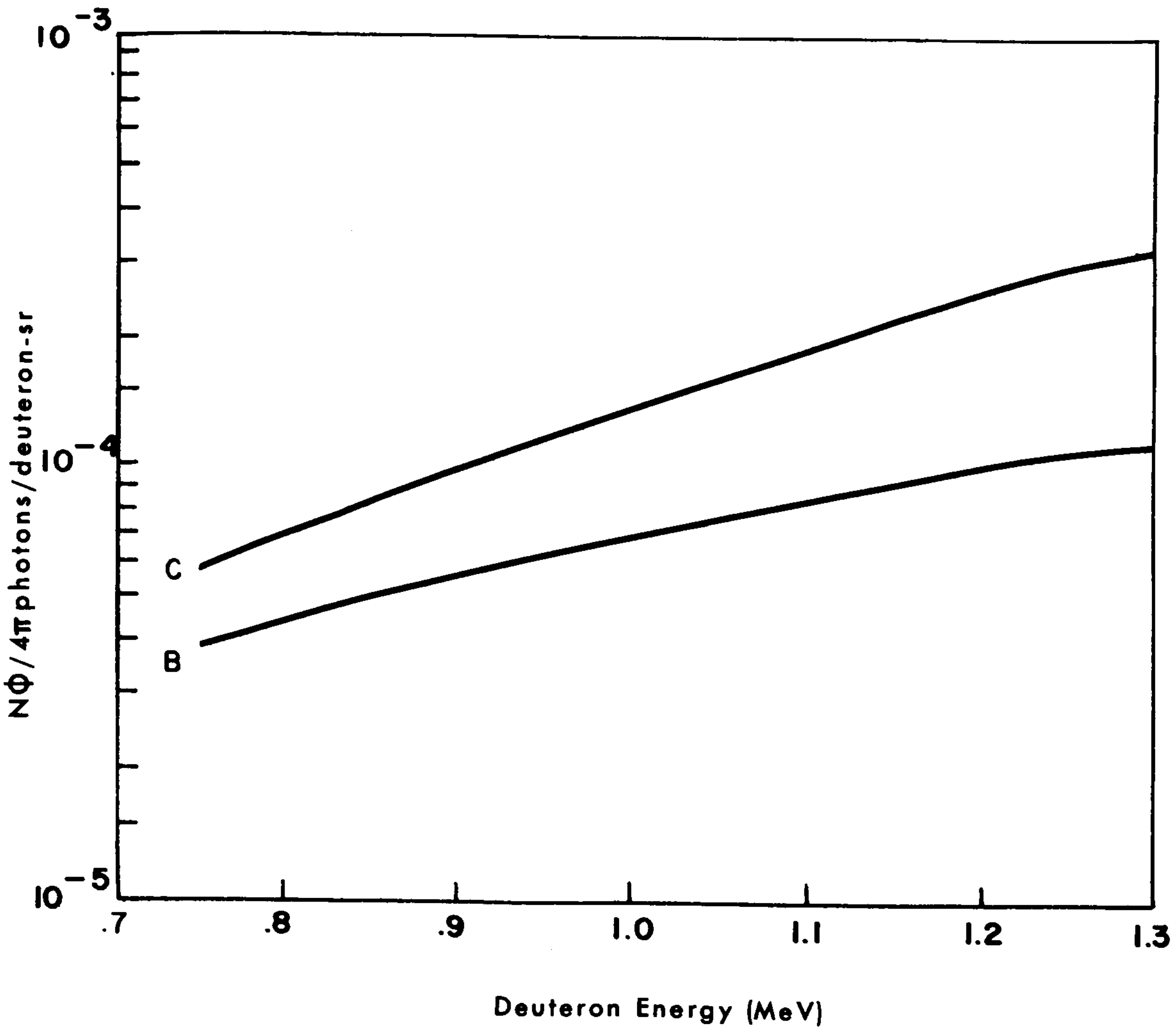

Figure 4.-Absolute photon yields of (B) boron K and (C) carbon K radiation for deuterons incident normal to the target and K shell x-ray take-off angle at 45°.

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